SEISMICITY AND SEISMOGENIC STRUCTURES IN CENTRAL APENNINES FROM TWO RECENT PASSIVE SEISMIC EXPERIMENTS: THE SLAM PROJECT (2009-2013)

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ABSTRAC As its long historical record shows, the portion of the Central Apennines which extends to the Tyrrhenian Sea margin and includes the Avezzano-Sulmona area to the north and the Isernia-Cassino area to the south, is affected by moderate to strong seismicity. In the last millennia three highly energetic events occurred: Venafro 1349, Boiano 1805 and Marsica 1915 with effect as large as I = X-XI *Mercalli - Cancani - Sieberg Scale* (MCS). More recently the study area was hit by the Val Comino seismic sequence (May 1984, *Mw* 5.9) at the border between Lazio and Abruzzo.

Two passive seismic experiments were carried out in the period between 2009 and 2013: the first one with 4 seismic stations (October 2009-January 2010) deployed in the Marsica-Sora area and the second one with 17 stations (November 2011-October 2013) deployed in the whole Central Apennines study area. These two arrays, together with the 20 stations of the Abruzzo regional seismic network (RSA) and the stations of the Italian seismic network (RSNC), have recorded in the study period 6742 earthquakes with local magnitude (M_L) ranging from 0.5 to 4.8. Temporary arrays data were integrated with the data of the two IESN (*Italian Experimental Seismic Network*) stations of southern Lazio and with those of the 5 stations of the Molise regional seismic network. The data considered in this study were recorded by a total of 74 seismic stations. We re-picked the arrival times of the events recorded by the RSNC and RSA and picked those recorded by the two temporary arrays. Our dataset consists of 39.322 P- and 32.600 S-arrival times. We read also *P*-wave first motion polarities to compute focal mechanisms. During the study period several seismic sequences occurred. Among these the most important are the Campoli Appennino sequence (September-October 2009) with 1299 events (M_L max 3.6) and the Sora sequence with 606 events (M_L max 4.8).

With this reviewed dataset we computed the best minimum 1-D velocity model for both V_p and V_s applying the *Velest* code. We compare and discuss the improved earthquake locations with the known seismogenic structures of the study area. The future planned activities will include the generation of high resolution 3-D tomographic models (V_p, V_s, Q_p, Q_s) of the fault systems, the relocation of all the studied seismicity with 3-D velocity models, the computation of the focal mechanisms, a review of the M_L and the mapping of *b-value*. Further studies could be on the temporal behaviour of observable seismic parameters, for instance the change in time of V_p/V_s during the seismic sequences.

SEISMOTECTONIC CONTEXT

The study region includes part of the central Apenninic chain and the peri-Tyrrhenian volcanic complex of Albani Hills and Roccamonfina. The tectonic features and the associated active fault systems in this area are the result of the Neogene-Quaternary evolution of the Tyrrhenian-Apennine system. **Figure 1** shows the main historical events that occurred in the area in the last millennium. The strongest earthquakes, such as the 1349 Venafro earthquake, the 1456 Molise-Campania event (the largest earthquake ever occurred in peninsular Italy), the 1805 Boiano event and the 1915 Marsica event, hit very large areas of central-southern Italy, causing effects of the XI degree on the MCS scale. The 1984 Comino Valley earthquake (*Mw* 5.9), the most important event recorded by instruments preceeding our observation period, hit thethe south-eastern Latium area (*Pace et al.*, 2002).

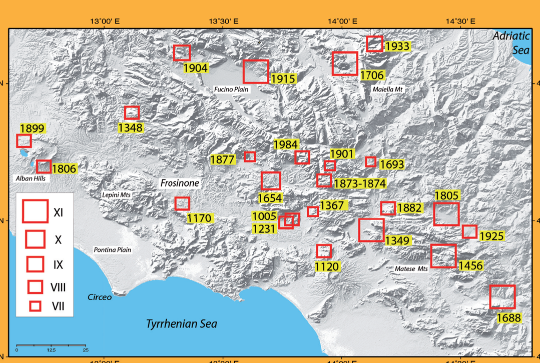

Figure 1. Historical seismicity from the CPTI11 (Catalogo Parametrico dei Terremoti Italiani, version 2011) database (*Rovida et al.*, 2011).

THE TWO PASSIVE SEISMIC EXPERIMENTS

We carried out a dense seismic survey of the study area using high-dynamic portable stations in continuous recording mode at a sampling rate of 125 *sps*. The first field experiment with 4 seismic stations started at the beginning of October 2009 and lasted up to the end of January 2010, and took place in the Marsica area at the border between Latium and Abruzzo. In the second field experiment (**SLAM** project, **S**eismicity of **L**atium - **A**bruzzo - **M**olise region) we deployed 17 portable seismic stations in the whole study area. This second experiment lasted from November 2011 to May 2013 with 17 stations and from June 2013 to October 2013 with 5 stations. **Figure 2** displays the station distribution of the two temporary arrays along with the existing permanent networks. Seismic station locations and operating period of the two experiments are listed in **Table 1**. The temporary stations were equipped with a high-dynamic (24 bit) Reftek RT130 digitizer, a three-component sensor, mostly extended-band Lennartz 3D/5s sensor (sensitivity of 400 V/m/s and velocity response flat in the range 0.2 - 40 Hz), a 12 V battery linked to a 70 W solar panel as power supply, and a 2Gb flash memory card as storage system. Data temporization was obtained by GPS signal.

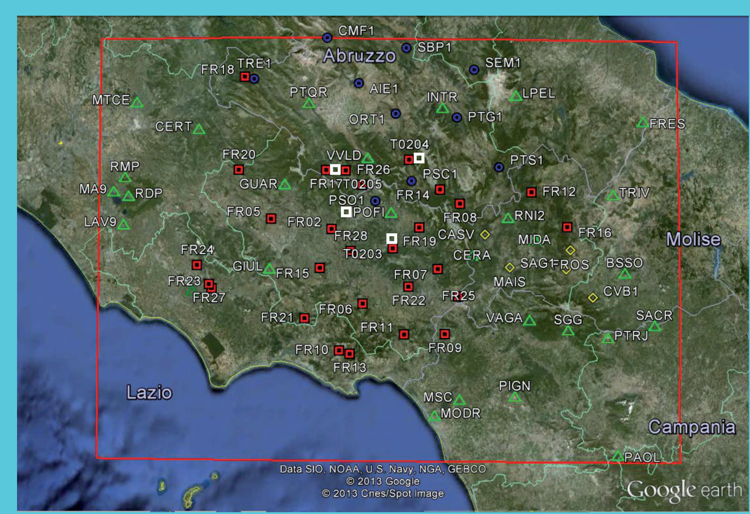

Figure 2. Seismic stations used in this study. White squares are the 4 stations of the Marsica experiment (2009-2010). Red squares are the temporary stations deployed for the passive experiment (SLAM project) between November 2011 and October 2013. Green triangles indicate the permanent stations of the Italian national network. Blue circles and yellow diamonds indicate respectively the Abruzzi and Molise regional networks.

Code	Location	Lat. (N)	Lon. (E)	Elev. (m)	Operating Period
T0203	Casalattico (FR)	41.61870	13.72131	562	04/11/2011 – 20/05/2013
T0204	Pescasseroli (AQ)	41.86654	13.72131	1376	02/11/2011 – 12/04/2012
T0205	Ridotti (AQ)	41.79539	13.60451	686	04/11/2011 – 30/11/2011
FR02	Casamari (FR)	41.67198	13.49025	266	04/11/2011 – 23/05/2013
FR05	Ferentino (FR)	41.69937	13.26305	387	12/11/2011 – 23/05/2013
FR06	Monte Leuci (FR)	41.46246	13.60844	478	18/11/2011 – 22/05/2013
FR07	Valvori (FR)	41.56089	13.89065	417	11/11/2011 – 21/05/2013
FR08	Barrea (AQ)	41.74404	13.97256	1182	14/11/2011 – 27/01/2012
FR09	Rocca d'Evandro (CE)	41.37758	13.91817	468	11/11/2011 – 17/08/2012
FR10	Itri (Sant. Civita) (LT)	41.33012	13.52067	642	03/11/2011 – 10/12/2011
FR11	Castenuovo Parano (FR)	41.37620	13.76489	465	01/12/2011 – 22/05/2012
FR12	Vastogirardi (IS)	41.77654	14.24302	1170	13/01/2012 – 20/05/2013
FR13	Itri (Rif. Tozze) (LT)	41.32087	13.56061	795	17/12/2011 – 22/04/2012
FR14	Civitella Alfedena (AQ)	41.78347	13.89761	1054	30/01/2012 – 21/05/2013
FR15	Pofi (FR)	41.56271	13.44679	141	23/02/2012 – 08/03/2013
FR16	Chiauci (IS)	41.67845	14.37870	940	02/03/2012 – 20/05/2013
FR17	Rendinara (AQ)	41.83607	13.46975	817	21/03/2012 – 30/10/2012
FR18	Carsoli (AQ)	42.09734	13.15863	485	16/11/2011 – 07/06/2012
FR19	Gallinaro (FR)	41.67727	13.82039	484	12/04/2012 – 21/05/2013
FR20	Piglio (FR)	41.83632	13.13841	856	24/04/2012 – 06/05/2013
FR21	Vallecorsa (FR)	41.42057	13.38977	326	22/05/2012 – 22/05/2013
FR22	Villa S. Lucia (FR)	41.51108	13.78065	346	09/06/2012 – 20/05/2013
FR23	Sezze Scalo(LT)	41.50267	13.03823	113	29/06/2012 – 16/08/2012
FR24	Valvisciolo (LT)	41.56753	12.98173	154	16/08/2012 – 08/11/2012
FR25	Radicosa (FR)	41.48366	13.96897	671	17/08/2012 – 21/05/2013
FR26	S. Giovanni V. R. (AQ)	41.83552	13.54277	304	30/10/2012 – 23/05/2013
FR27	Sezze - Casali (LT)	41.51420	13.02805	417	09/11/2012 – 29/04/2013
FR28	Fontana Liri (FR)	41.61039	13.56237	379	08/03/2013 – 23/05/2013

Table 1. Location parameters and operating periods of the Marsica experiment and SLAM temporary stations.

SEISMIC RECORDINGS AND ANALYSIS

During the period January 2009 - October 2013, we collected seismic recordings from 6742 local earthquakes. In a first step all this seismicity was relocated using the Hypoellipse location program (*Lahr*, 1999) and a regional 1-D velocity model with a fixed V_p/V_s ratio of 1.80. The arrival times dataset consists of 39322 P-wave picks and 32600 S-wave picks. **Figures 3** and **4** display the relocated hypocenters respectively within the whole study area and within the zone where over 51% of the examined seismicity occurred, i.e., the Sorano-Marsica area. Figure 4 also shows 25 well-constrained P-wave first motion focal mechanisms computed by using the FPFIT code (*Reasenberg and Oppenheimer*, 1985) (see also **Table 2**). **Figures 5** to **7** give a close look on the main seismic sequence of the study period: the February 16, 2013 earthquake and related aftershocks activity. The mainshock (**Figure 5**) was preceded by some deep foreshocks (hypocentral depth around 20 km) recorded the previous day.

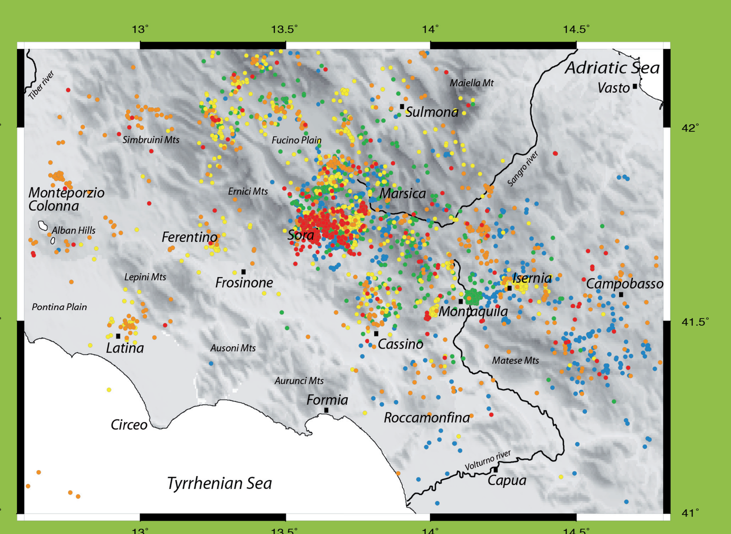

Figure 3. Map view of the relocated seismicity (6742 events; average rms 0.12s) which occurred within the study area from January 2009 to October 2013. Earthquakes were relocated using P- and S-wave arrival times handpicked from continuous recordings of the integrated network shown in **Figure 2**. Coloured dots differentiate the seismic activity through tgtime (2009, blue dots, 2275 events; 2010, green dots, 1105 events; 2011, yellow dots, 1568 events; 2012, orange dots, 679 events; 2013, red dots, 1115 events). The three main sequences recorded during our observation period are located in the Sorano-Marsica area. The first two sequences occurred near the town of Campoli Appennino, in September-October 2009 and May 2011. The third sequence is associated to the recent M_L 4.8 Sora earthquake (February-May 2013). The green cluster in the upper Volturno Valley shows the May 2010 Montaquila seismic sequence, while the orange one, to the north of the Alban Hills, shows the Monteporzio-Colonna sequence of June-July 2012. Finally, the yellow-orange clusters in the Pontina Plain are the two small sequences of July 2011 and February 2012, respectively.

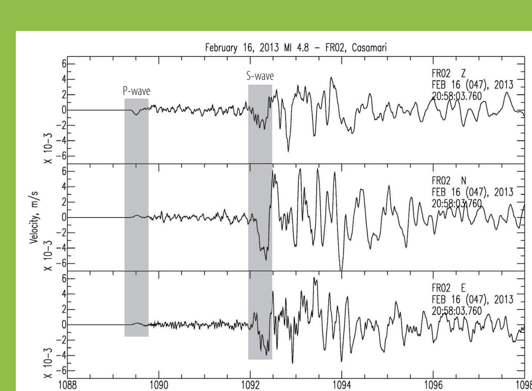

Figure 5. Seismograms of the February 16, 2013 earthquake recorded at the closest station of the SLAM array. Station FR02 (Casamari) was located about 10 km from the epicenter in the SW direction.

N	Date	UTC time	Lat. (N)	Lon. (E)	Depth (km)	Strike	dip	Rake	N. of Polarities	Q_f	Q_p	M_L
1	06-08-2009	15:36	41 38.78	13 41.03	16.94	150	40	-90	25	A	A	4.2
2	30-09-2009	19:52	41 43.48	13 42.27	15.01	20	55	-80	38	A	A	3.5
3	06-10-2009	19:38	41 44.20	13 42.51	12.91	110	55	-90	23	A	A	3.1
4	07-10-2009	04:44	41 44.05	13 42.24	13.14	125	50	-100	20	A	A	3.2
5	08-10-2009	00:51	41 44.48	13 42.75	12.29	20	35	-90	31	A	A	3.6
6	08-10-2009	19:14	41 43.95	13 42.24	11.73	110	40	-90	10	A	A	1.4
7	09-10-2009	19:27	41 43.83	13 42.22	11.74	105	35	-90	11	A	A	1.2
8	05-05-2011	02:19	41 45.09	13 43.44	14.85	345	25	-60	17	A	A	2.1
9	05-05-2011	03:34	41 45.00	13 43.76	15.09	90	65	-90	18	A	A	2.1
10	06-05-2011	02:06	41 45.06	13 43.42	14.72	80	55	-100	19	A	A	1.9
11	06-05-2011	16:14	41 44.92	13 43.87	14.89	130	70	-100	17	A	B	2.0
12	08-05-2011	22:39	41 44.92	13 43.89	14.87	325	25	-80	21	A	A	2.2
13	08-05-2011	22:58	41 44.93	13 43.83	14.03	345	15	-60	16	A	A	1.7
14	09-05-2011	03:48	41 45.35	13 43.77	13.80	115	60	-110	17	A	A	1.9
15	18-05-2011	17:58	41 44.97	13 43.76	14.59	140	40	-90	13	A	B	2.4
16	16-02-2013	21:16	41 43.47	13 34.35	20.77	175	65	-60	92	A	A	4.8
17	16-02-2013	22:24	41 43.19	13 36.15	17.90	175	50	-60	33	A	A	2.3
18	17-02-2013	17:27	41 45.10	13 37.07	15.58	110	50	-90	26	A	A	2.2
19	20-02-2013	19:16	41 42.99	13 35.27	19.23	165	45	-40	20	A	B	1.6
20	23-02-2013	05:02	41 44.48	13 38.13	13.52	150	35	-90	25	A	A	2.0
21	23-02-2013	10:27	41 44.62	13 38.16	13.31	175	45	-70	36	A	A	2.8
22	23-02-2013	16:30	41 44.52	13 38.29	14.33	125	50	-120	23	A	A	2.0
23	23-02-2013	16:36	41 44.59	13 38.04	13.45	135	60	-80	23	A	A	2.1
24	23-02-2013	17:17	41 44.52	13 38.18	13.28	325	25	-120	42	B	A	3.1
25	23-02-2013	18:02	41 44.70	13 37.78	12.78	115	50	-120	19	A	B	1.8

Table 2. Fault plan solutions, Sorano-Marsica area 2009-2013.

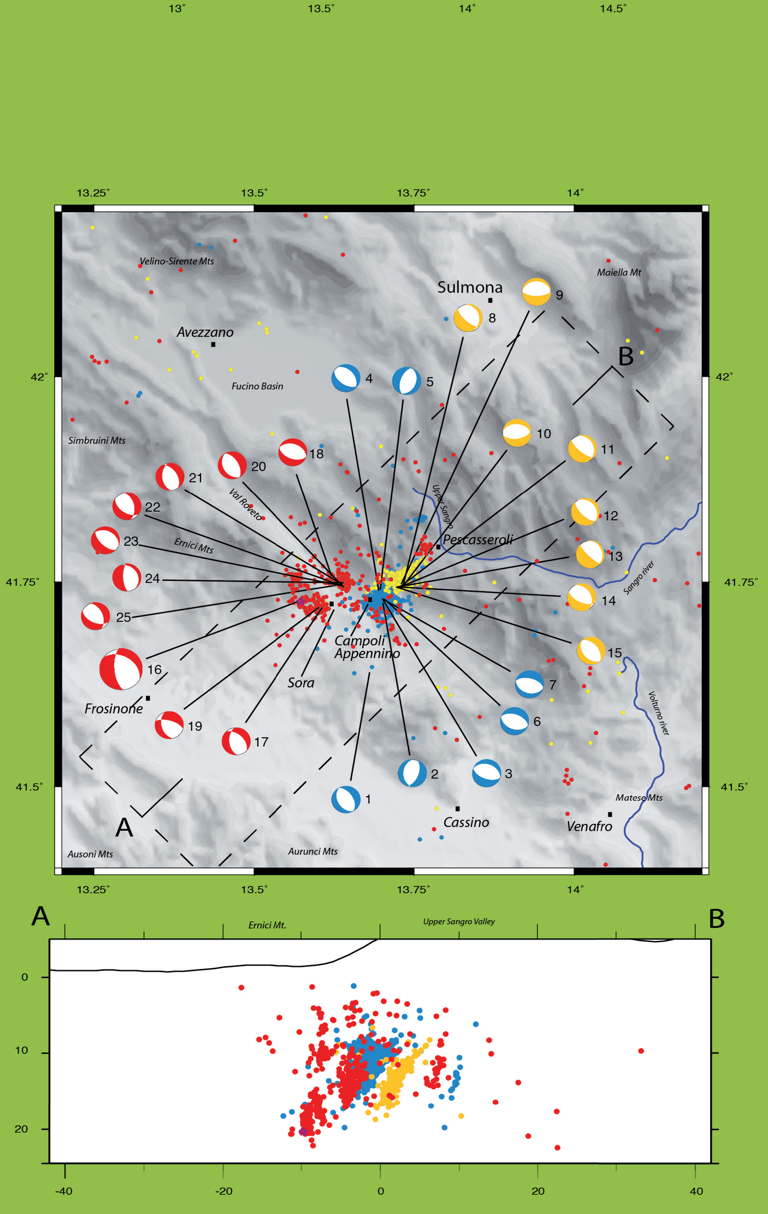

Figure 4. Map view and SW-NE cross-section of the seismicity relocated in the Sorano-Marsica area (2677 events, the 40% of the total studied seismicity; average *rms* 0.11s). Blue dots indicate the first Campoli Appennino sequence (September-October 2009; 1299 events), yellow dots the second Campoli Appennino sequence (May 2011; 772 events), and red dots the Sora sequence (February-May 2013; 606 events). Focal mechanisms for a set of 25 events are also displayed. The largest red beach-ball (number 16) is the focal mechanism of the February 16, 2013 Sora earthquake. Most of the fault plane solutions have pure dip-slip kinematics with nodal planes oriented NW-SE in agreement with the anti-apenninic extensional regime. The N-S nodal plane of the M_L 4.8 event shows a high-angle dip to the W consistent with the deeper cluster (13-21 km of depth) of the Sora sequence. In the map view, the two Campoli Appennino sequences (blue and yellow) partially overlaps, nevertheless the SW-NE cross section clearly shows two planes dipping to the SW with an angle of about 50°. Two small clusters with an high-angle dip (around 70°) are located close to the upper Sangro Valley (nearby the town of Pescasseroli) and were recorded during the 2009 and 2013 sequences, respectively. The seismicity of the 2013 (red dots) is characterized by a gap between the two main clusters of this sequence at around 13-18 km of depth. The 2013 sequence is located to the west of the two Campoli Appennino sequences, beneath the southeastern tip of the Ernici mountains.

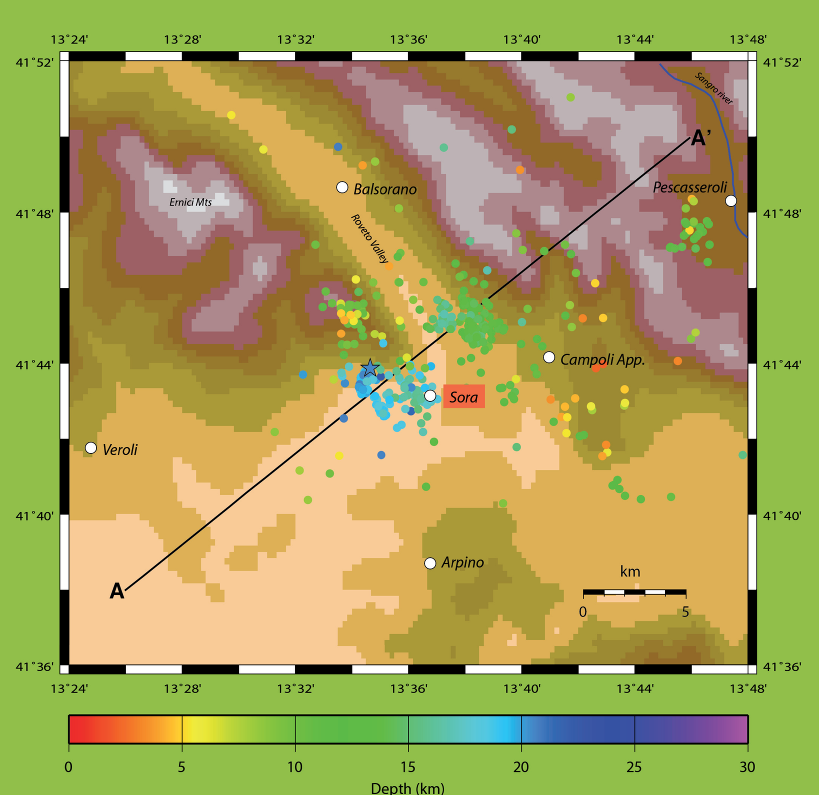

Figure 6. Seismic activity recorded in the area surrounding the city of Sora between February and May 2013. Blue star indicates the M_L 4.8 epicentral location. The black line AA' identify the cross-section profile represented in *Figure 7*.

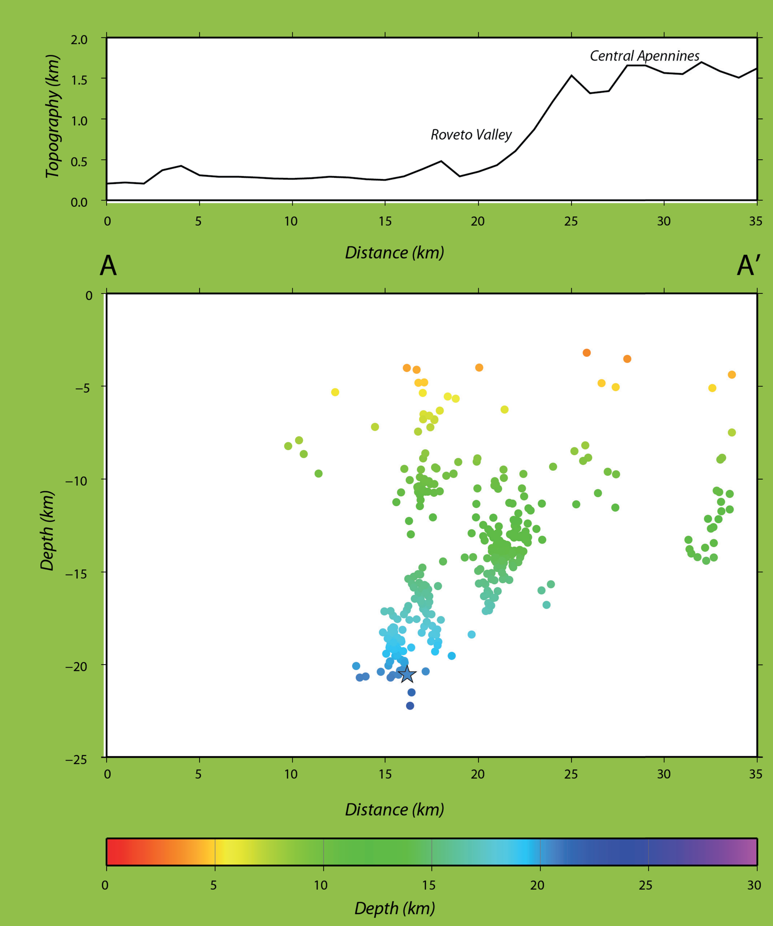

Figure 7. SW-NE cross-section with hypocentral depth distribution. The location displayed on the plot are those with an horizontal distance ≤ 5 km from the vertical profile. The mainshock (blue star) is located at about 21 km depth, in the deeper part of a recognizable SW-dipping seismogenic structure.

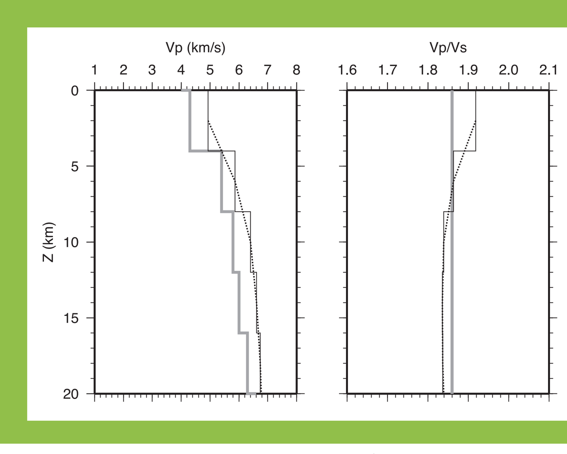

Figure 8. Starting (thick line) and final (thin line) P wave minimum 1-D velocity model computed with the *Velest* code (*Kissling et al.*, 1994).

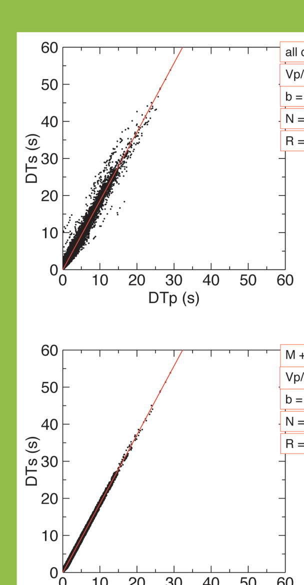

Figure 9a and 9b. Wadati diagrams. Linear fit of DTs versus DTp (*S* and *P* wave differential travel time measurements, respectively): 9b) with all data; 9b) the best fit (without data with residual larger than ±2σ). The linear fit gives a V_P/V_S ratio of 1.86 while the correlation coefficient is 0.99.

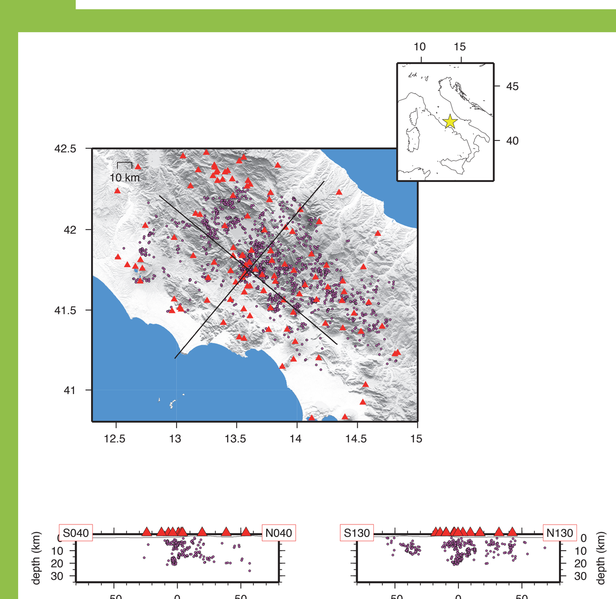

Figure 10. Epicentral relocation of all the dataset using the velocity model computed with the *Velest* code and 1.86 for the V_P/V_S ratio. Seismic stations are plotted with red triangles.

References

Kissling, E., W.L. Ellsworth, D. Eberhart-Phillips, and U. Kradolfer (1994). Initial reference models in local earthquake tomography, J. Geophys. Res., 99, 19,635-19,646.

Lahr, J.C., (1999). HYPOELLIPSE: a computer program for determining local earthquake hypocentral parameters, magnitude, and first-motion pattern, *USGS Open-File Report 99–23*, version 1.1, 119 pp.

Pace, B., Boncio, P., and Lavecchia, G., (2002). The 1984 Abruzzo earthquake (Italy): an example of seismogenic process controlled by interaction between differently oriented synkinematic faults, *Tectonophysics*, 350, 237-254.

Reasenberg, P., and D. Oppenheimer, (1985). FPFIT, FPPLOT and FPPAGE: FORTRAN computer programs for calculating and displaying earthquake fault-plane solutions, *USGS Open-File Report*, 85-739.

Rovida, A., Camassi, R., Gasperini, P., e Stucchi, M., (a cura di), (2011). CPTI11, la versione 2011 del Catalogo Parametrico dei Terremoti Italiani. Milano, Bologna, http://emidius.mi.ingv.it/CPTI. DOI: 10.6092/INGV.IT-CPTI11.